Influence of head movements on sound localization with cochlear implants

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Abstract: Bilateral Cochlear Implant (CIs) users encounter difficulties to localize sound sources in realistic environments, especially in the presence of background noise. They show significant directional errors and large front-back confusions occur compared to normal hearing subjects in the same conditions. To date, most past studies have been carried out in mostly quiet laboratory settings with fixed head positions. Real-world sound localization is usually done in much more complex acoustic environments with the presence of noise and reverberation. In such circumstances, head movements provide essential additional information about the position of a source. We know that the normal hearing listeners use differences in interaural information provoked by head movements to resolve ambiguities in source position, especially front back confusions. It is however still unknown to what extent CI users can take advantage of head movements and how much it helps for sound localization.In order to evaluate CI users in realistic conditions, we simulated a noisy cafeteria using 12 loudspeakers set up in a circle with a diameter of 3m. We asked the test subjects to localize a male speaker in cafeteria noise. They were instructed to move their head freely in the horizontal plane. The test subjects were equipped with a head tracking sensor to monitor their head movements. The length of the speech signals was varied to limit the range of possible head movements. The speech signals were taken from the OLSA test material. Three signal durations were implemented from 460ms (one name) to 2.16s (one sentence). Two signal-to-noise ratios were tested to cover quiet and noisy environments: 15 and 0 dB SNR. Additionally, the experiment was repeated with the test subjects instructed to keep their head fixed.Pilot results show an increase in localization performance when head movements are allowed. The CI users were however not able to resolve all the front-back confusions, in contrast to normal hearing listeners who could perform this task easily. We noticed large differences in performance and head trajectories between the subjects indicating that not all CI users tested could take advantage of the variations in interaural information.

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Influence of head movements on sound localization with cochlear implants

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Introduction

Bilateral Cochlear Implant (CI) users encounter difficulties to localize sound sources in realistic environments, especially in the presence of background noise. They show large directional errors and front-back confusions compared to normal hearing subjects in the same conditions. To date, most studies have been carried out in quiet laboratory settings with fixed head positions. Real-world sound localization is usually done in much more complex acoustic environments with the presence of noise and reverberation. In such circumstances, head movements provide essential additional information about the position of a source. We know that the normal hearing listeners use differences in interaural information provoked by head movements to resolve ambiguities in source position, especially front back confusions [1-4]. It is however still unknown to what extent CI users can take advantage of head movements and how much it helps for sound localization.

To evaluate the ability of bilateral CI subjects to take advantage of head movements an experiment has been designed whereby the test subjects had to localize target speech signals of different lengths. The hypothesis was that longer duration target signals would benefit from head movements and thus the variation in interaural information would be larger than for short duration stimuli. To get closer to real-world situations, a diffuse background noise was played through an array of loudspeakers around the test subjects. To record and monitor the head movements, we used a head motion tracker. A similar head tracker has been tested in [5] and no interference between the cochlear implant and the motion sensor had been found.

Method

The task of the test subjects was to localize a target male speaker in a diffuse background cafeteria noise. The speech material was taken from the OLSA test database. Three different signal lengths were used, consisting of single words, single sentences and two sentences for Short, Middle and Long durations respectively. For each signal length, six different signals were chosen and presented in random orders. This was done in order to prevent the listener from tuning into a particular stimulus. The speech signals were selected to have the most uniform length and loudness as possible across test conditions. The average durations of the signals were 503 ms, 2.18 s and 4.45 s for the Short, Middle and Long durations respectively. The cafeteria noise was played incoherently from twelve loudspeakers located at 1.5 meters around the listener. The level of the background noise was set to 60 dB SPL and measured with a sound level meter at the centre of the loudspeaker ring. The level of the target speech was set to the level of the noise based on their respective RMS values. To ensure that the listeners could not identify a loudspeaker based on a specific coloration or intensity difference, the level of the target was roved by 2 dB between successive presentations.

A typical test session consisted of two blocks of three conditions. In each block the test subject was instructed either to keep his/her head still or to move the head in the horizontal plane. In each condition, speech signals of a given length were used. Testing in each condition consisted of an initial training phase with feedback where every position was played once in random order. The training was followed by a test run, in which every position was played twice. At the beginning of every block an orientation sequence was played, in which the signal of middle length was played from position to position, starting from the front and moving counter-clockwise. During this phase the listeners were asked to pay close attention to the position of the source. The order of the blocks and test conditions was randomized between subjects. A typical test block lasted 30 minutes. It was followed by a break and then the second test block. The subjects were asked to come for a retest session on another day. In total, the experiment required two sessions of one and a half hours each. The test-retest analysis did not show any training effect between both sessions.

Eleven normal hearing subjects and seven bilateral CI users took part in the experiment. The hearing loss of the normal hearing was measured by standard clinical audiometry and did not exceed 20 dB hearing loss across all frequencies. The inclusion criterion for CI subjects was simply to be bilaterally implanted.

Analysis of head trajectories

For conditions with head movements, the head trajectories were recorded with the motion-sensor fixed on the top of the head of the subjects. To analyze the differences in head movements between normal hearing subjects and CI users, the trajectories were defined by the time until a response was given, the total length of motion and the number of movements towards the wrong direction. The measures analyze the head trajectories after a 3° movement from the initial and ending positions so that the reaction and response reporting times did not influence the results.

Results

The outcome of the localization experiment is shown in Fig. 1 for the amount of front-back confusions (top graph, in [%]) and the angular RMS errors (in [°]). As expected, the CI users performed worse than the normal hearing subjects for all test conditions. For the CI subjects and the conditions without head movements, a similar percentage of front-back confusions occurred independently of signal length (around 25%). This contrasts with the data from the normal hearing subjects, where confusions decreased with increasing signal duration. The differences between the distributions of the results for the short signals and the middle and long sentences were highly significant ($p = 0.007$). During the “fixed head" conditions, head movements were monitored. It appeared that, while the listeners were instructed to keep their head still, small head movements between three to five degrees occurred. Those movements might have helped the normal hearing subjects but not the bilateral CI users and could explain the reduction of front-back confusions.

For all listeners, head movements significantly helped to distinguish between front and back positions, provided the target sentences were long enough. For the CI users, the amount of front-back confusions dropped from 23.6% to 10.4% and from 25% to 5.5% for the middle and long signals respectively. These differences were highly significant ($p < 0.01$). While listening to the short signals, the listeners were encouraged to move their heads even if it appeared counter-productive. Indeed, some CI users reported that head movements disturbed more than helped, because of the short duration of the test signals. They indicated more front-back confusions with head movements than without (31.4% against 26.4%). This effect was however not significant. For the normal hearing subjects, head movements removed all front-back confusions for the middle and long sentences. For the short signals, there is a trend indicating that the normal hearing listeners could have used head movements for a better performance. The difference was not significant ($p = 0.06$).

The angular RMS errors are shown in Fig. 1 (bottom graph). Interestingly, the head movements did not improve the results of the CI users. The mean RMS errors were 30.6°, 26.9° and 27.6° for the short, middle and long signal lengths respectively. This was quite surprising, as we expected for the long signals at least, an increase in performance. In this condition, the listeners had enough time to scan the room and look for the target sound source. Normal hearing subjects on the other hand showed statistically significant lower RMS errors for the middle and long signal durations when head movements were allowed.

The uncertainty in sound localization of the bilaterally implanted CI subjects was clearly visible in the more erratic characteristics of their head trajectories. In all trajectory measures (see Fig 2.), they scored worse than the normal hearing subjects. The total length of movement (Fig. 2, top) was greater for CI subjects for the middle and long target signal durations. However, this was significant for the long signals only. For the normal hearing subjects, the trajectory range and length did not differ between middle and long stimuli. This indicates that increasing the duration of the stimulus did not provide more useful information. A similar pattern can be seen when looking to the response delay of the test subjects (Fig. 2, middle). The CI users score higher for all conditions. Statistical significance was reached only for the middle and long signals ($p < 0.001$). By looking at the movements towards the wrong directions (Fig. 2, bottom), the higher uncertainty in the movements of the CI users is clearly visible. They rotated their heads in the wrong direction for all test conditions and more so when listening to long signals. This was seldom the case for the normal hearing subjects. Some listeners however reported focusing on the target loudspeaker with the appropriate ear and used the difference in signal to noise ratio as a cue for localization.

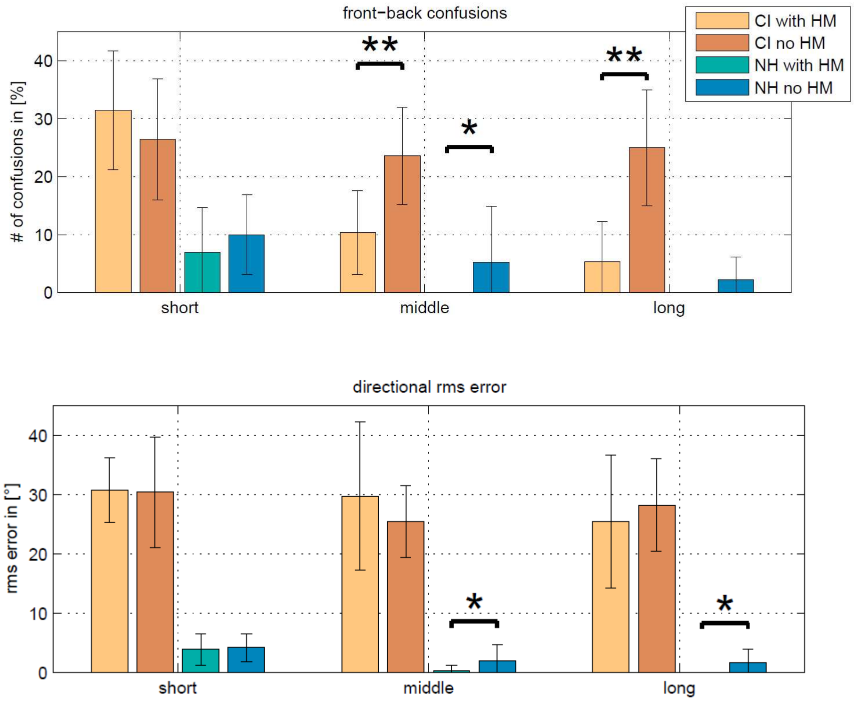

Figure 1: localization performance of the CI users (orange) and normal hearing subjects (blue). The rate of front-back confusions is shown in the upper graph, the directional RMS error in the bottom.

Discussion and conclusion

The results presented in this paper confirm our hypothesis that head movements are essential to bilateral CI users for localization. They allow distinguishing between sounds played from the front versus back. In the most favourable test situation, the proportion of front-back confusions was reduced from 25% to 5.5%. This score is of the same order than the performance of normal hearing subjects for signals of medium length with fixed head position. The results suggest however, that some confusions could not be resolved, even with very long listening time. For the long signals, the signal duration was 4.45 seconds in average, which is long enough to scan the entire loudspeaker ring with head movements to locate the appropriate loudspeaker.

The head movements and the signal duration had practically no effect on the angular RMS errors of the CI users. The error was around 28° for all conditions and was significantly higher than what other studies have reported (9.8° in [6] for example). The presence of background noise could explain this difference, although the target signal was always clearly audible and reported as such by the test subjects. Seeber and Fastl [7] suggested that the CI users primarily use differences in level for localizing sound sources. The background noise could have masked the speech signal in the contralateral ear in regions where the head shadow effect was large and thus reduced performance.

Head movements can have a positive effect on speech understanding as well. It is however still unknown how large this benefit is for bilateral cochlear users, especially in more complex acoustical settings, such as noisy and multi-talker environments. The real benefit CI users extract from their devices would probably be higher than shown by classic clinical speech intelligibility tests. Further experiments that combine head movements and visual information are needed to clarify this point.

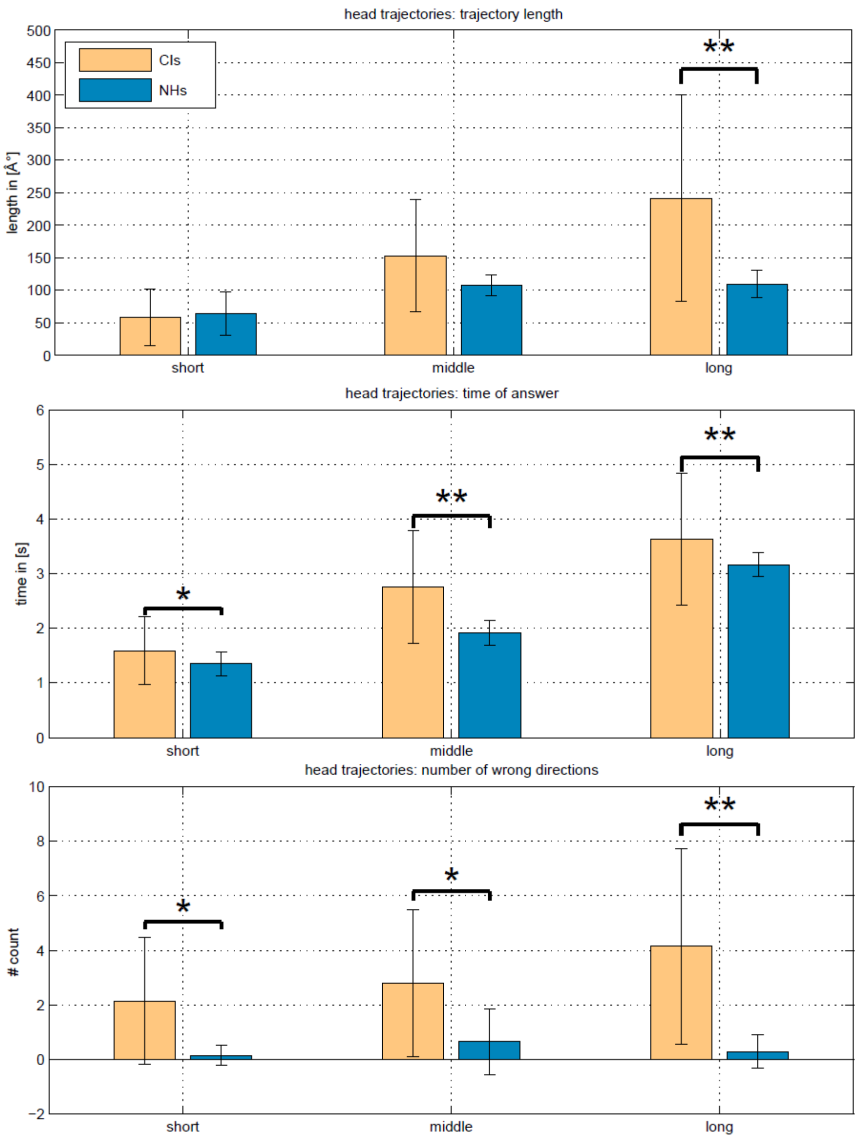

Figure 2: Analysis of the head trajectories of the CI users (orange) and normal hearing listeners (blue) for the short, middle and long signal durations. The trajectory lengths are shown in the top, the response time in the middle and the number of movement to the wrong direction in the bottom.

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